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Evaluation of site impacts associated with three silvicultural prescriptions in an upland hardwood stand in northern Alabama, USA

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Abstract

Soil disturbance patterns and associated changes in soil physical status were measured in a study that evaluated the implementation of three alternative management prescriptions in an upland hardwood stand in northern Alabama, USA. Management prescriptions applied in this study consisted of a clear-cut, strip cut, and deferment cut that were compared to a non-harvested control. Final tabulations of disturbance types indicated disturbance to be similar in clear-cut and deferment cut treatments with less disturbance in strip cut sites. Soil physical response varied by soil property but, in general, as disturbance intensity increased, soil physical properties responded accordingly. Bulk densities were elevated to the highest degree in the clear-cut sites while soil strength as indicated by cone index measurements attained its highest levels in the deferment cut. These differences were thought to be due to differences in trafficking patterns related to the implementation of each management prescription.
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Keywords: Soil compaction; Bulk density; Soil strength; Hardwood; Alabama; Clear-cut; Cone index

1. Introduction

Even age management (e.g., block clear-cuts) is commonly employed in upland hardwood stands of the southern Appalachian and mid-South areas of the southeastern USA to minimize costs and encourage regeneration of higher quality, shade intolerant trees [1–2]. A significant drawback to clear-cutting is the degree of machine impacts such as ruts, skid trails, and trafficked areas and changes in soil physical status [3–7]. The overall result is increased risk of erosion, lowered site productivity, and loss of esthetic qualities [4,8–10].

The replacement of clear-cutting for regeneration necessitates the identification of silvicultural options that have less impact on the local environment while promoting adequate regeneration of desired species. Alternative management prescriptions have been successfully employed in regeneration of northern and bottomland hardwoods (strip cutting) and resulted in reductions in site and soil impacts in mixed hardwood stands (single tree selection and shelterwood) [11–13]. Less site disturbance contributes to successful regeneration of upland hardwood species and the maintenance of overall site quality [4,14].

Soil disturbances have been assessed through either the tabulation of previously defined disturbance categories that accurately describe surface disturbances and/or measurement of changes in soil properties, primarily physical, in response to machine trafficking [6,10,15–17]. The utilization of both methods, either singly or in combination, can yield important information regarding harvesting impacts as well as providing comparisons among specific silvicultural prescriptions, harvesting methods and equipment, and/or site characteristics. The results of these studies may eventually provide important information on the interaction between soil impacts and tree regeneration in upland hardwood stands.

The objectives of this study were to conduct: (1) an assessment of soil surface disturbance patterns and changes in soil physical properties associated with three management prescriptions in an upland hardwood stand in

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northern Alabama; (2) a comparison of impacts associated with each management prescription; and (3) an evaluation of the relationship between changes in soil physical properties and visually determined disturbance classes (DICL).

2. Materials and methods

2.1. Study and site description

The study site was located in an upland hardwood stand on the southern boundary of the Cumberland Plateau near Moulton, Lawrence County, Alabama within the administrative boundaries of the Bankhead National Forest. The study area encompassed approximately 22 ha of hardwood forest classified as an oak-hickory association with a stand density of 924 trees ha^{-1} and a basal area of $30\,m^2\,ha^{-1}$ on north and south facing slopes of approximately 20–25% steepness. Treatment (TRT) areas were established on both aspects of a single ridgeline with 15 ha located on north-facing slopes and 6 ha on south-facing slopes. The study site was previously owned and managed by Champion International Corporation whose personnel were instrumental in the installation of TRTs. Currently, the site is owned and managed by International Paper Company.

The experimental design consisted of a randomized complete block design with three replications and four TRTs. TRTs were clear-cut (CC), strip clear-cut (SC), deferment cut (DC), and a non-harvested control (CON). Silvicultural TRTs were installed in 1.6 ha blocks in six locations along the northern aspect of a select ridgeline and three locations of similar size along the southern aspect (Fig. 1). A non-harvested CON TRT approximately 0.8 ha in size was included within each replication. CC TRTs were defined as removal of all stems greater than 0.038 m diameter at breast height (DBH) throughout the harvest block. SCs were defined as removal of stems greater than 0.038 m DBH in strips approximately 37 m wide between non-harvested strips (US) of similar dimension. DCs involved removal of all stems except for approximately 5.7-m^2 basal area per hectare of healthy, high-quality trees throughout the TRT area and removal of all other stems. Soil types within the study area were derived from parent materials composed of sandstone, shale, and interbedded areas of sandstone and shale; soil series were typically classified as Typic Hapludults but members of Hapludalfs and Dystrudepts were also present. Installation of TRTs commenced in July 1996 and was completed by September 1996.

2.2. Site measurements

2.2.1. Pre-harvest

Each treated area was delineated into 1.6 ha blocks measuring 122 × 134 m from which soil samples were removed and in situ measurements made for the characterization of soil physical properties prior to the installation of TRTs. A point grid system was superimposed on each TRT area (24 × 48 m) and a total of 30 intact cylindrical soil cores (0.051 × 0.051 m) were collected from soil surface horizons. Intact soil cores were analyzed for bulk density and soil moisture content (SMC) by weight while bulk soil

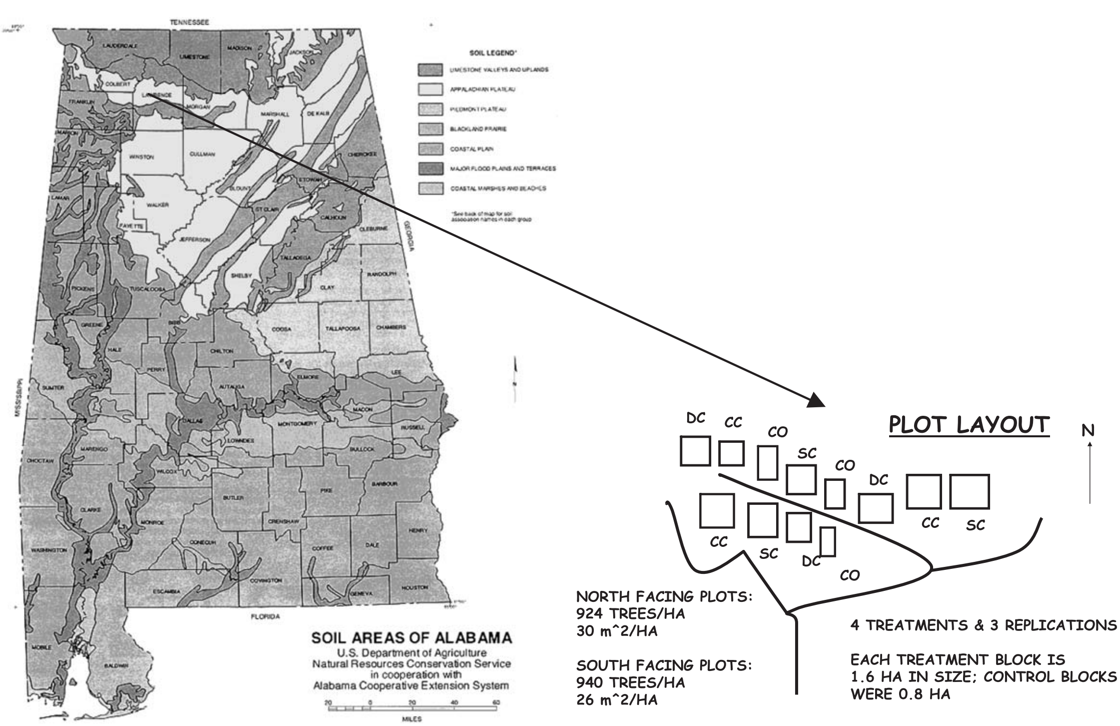

Fig. 1. Location and plot layout of study assessing the effects of three alternative management prescriptions in an upland hardwood stand in northern Alabama, USA.

samples were collected for determination of particle size by the pipette method. Soil physical analyses were performed in accordance with Klute [18]. Similarly, in situ measurements of soil strength were collected at each grid point location using a Rimik CP20 recording cone penetrometer to a depth of 0.20 m, recorded in 0.025 m increments, and the final results reported as cone index (CI) values [19]. Pre-harvest sampling was conducted in Spring, 1996.

2.2.2. Post-harvest

After TRT installation, a point grid system of higher resolution was superimposed on each TRT area (12×24 m) for a total of 60 grid points to be sampled and included the previously sampled grid point locations. Soil disturbance was assessed by assigning a pre-defined DICL at each grid point location in each TRT block. DICLs assigned in this study were similar to those defined by Miller and Sirois [16] and consisted of the following:

Untrafficked (UNT)

Slightly disturbed

- trafficked with litter in place (2A)
- trafficked with litter removed (2B)
- trafficked with mineral soil exposed (2C)
- trafficked with mineral soil displaced to top of litter (2D)

Disturbed

- surface soil removed and subsoil exposed (3A)

Highly disturbed

- soil depressions less than 0.15 m (4A)
- soil depressions between 0.15 and 0.30 m (4B)
- soil depressions greater than 0.30 m (4C)

Non-soil (NS)

The final tally of DICLs consisted of relatively few grid points assigned to categories 2C, 2D, 3A, and 4C. The final revised DICL scheme consisted of the following:

Untrafficked (UNT)

Slightly disturbed (SD)

- trafficked with litter in place (2A)
- trafficked with litter removed/mineral soil exposed (2B)

Highly disturbed (HD)

- depressions less than 0.15 m
- depressions greater than 0.15 m

Non-soil (NS)

Grid points classified as 2C, 2D, and 3A were compiled into 2B and DICLs recorded as 4B and 4C were grouped into class 4B. Final results for soil DICLs detected in the SC TRT are presented on a stand wide (SW) basis, harvested strips (HS) alone, and US alone.

Soil samples were collected in all grid points where possible and analyzed for bulk density and gravimetric SMC according to previously cited methodology [18]. Soil strength data were collected in situ at the time of soil sampling with the Rimik CP 20 recording cone penetrometer at all grid locations as similarly described. Soil physical properties in SC TRT are presented on a SW basis, harvested strip, and in non-harvested basis as previously described.

2.2.3. Data analysis

Area percentages of each DICL by TRT were calculated by summing the number of points for each DICL in each TRT block and dividing by the total number of points over all replications. Percentages of the non-harvested CON were computed using fewer points due to the smaller dimensions of the TRT plots.

Soil bulk density and SMC were analyzed in an analysis of variance (ANOVA) (PROC GLM) ($\alpha = 0.05$) with DICL as a split plot in two depth increments (0–0.10 and 0.10–0.20 m) for significance as a result of TRT, depth, DICL and their interactions. Postharvest CI values were averaged for each TRT and replication combination in 0.025 m increments of depth and the change in CI with depth analyzed in a least-squares regression (PROC REG). Regression parameters related to slope and y intercept were analyzed by comparing regression coefficients to determine if differences among TRTs, depth, DICL and their interactions were detectable. Means separation were performed by a Duncan's Multiple Range Test at $\alpha = 0.05$ when significance was detected; means separated at a higher level of significance are noted when appropriate. The interaction of TRT $\times$ DICL was not significant as indicated by low r^2 values. All statistical evaluations and comparisons were conducted using the Statistical Analysis System (SAS Institute, Inc.) [20].

3. Results

3.1. Pre-harvest

Pre-harvest soil characterization indicated some differences in bulk density, SMC, and CI values in the soil surface layer averaged by slope position or future management prescription (Table 1). In general, bulk density values of approximately 1.0 Mg m^{-3} and CI values of less than 1.00 MPa were measured throughout the study site. However, elevated levels of bulk density values were detected in the areas designated for the DC TRT and measured approximately 1.14 Mg m^{-3} when examined by slope position. Differences in SMC were detected by slope position with the greater moisture content measured in the bottom slope position; SMC by TRT area revealed slight differences in moisture content with the SC TRT area slightly drier. CI values of approximately 0.75 MPa were

Table 1
Surface soil physical characteristics of an upland hardwood stand by slope position and future management prescription, northern Alabama, USA

	Bulk density ($Mg\,m^{-3}$)	Soil moisture content (%) (w/w)	Cone index (MPa)	Texture
Slope position				
Summit/shoulder	0.97 (25.7)[a]	20.7 (38.4)	0.71 (65.6)	Loam
Sideslope	1.00 (23.6)	24.8 (33.5)	0.74 (60.7)	Loam
Toeslope	1.03 (23.4)	26.5 (26.5)	0.72 (85.0)	Loam
Future management prescription				
Clear cut	0.94 (26.6)	22.1 (28.5)	0.78 (72.4)	—
Strip cut	0.94 (23.5)	21.2 (45.1)	0.54 (66.9)	—
Deferment cut	1.14 (21.4)	24.5 (28.6)	0.92 (60.2)	—

[a]Number in parentheses is coefficient of variation (CV).

Table 2
Soil disturbance assessment of three alternative management prescriptions in an upland hardwood stand, northern Alabama, USA

Disturbance class	Treatments				
	Clear cut (%)	Deferment cut (%)	Strip cut[a]		
			SW	HS	US
Untrafficked (UNT)	18	20	62	25	71
Slightly disturbed (SD)					
2A	33	30	18	35	13
2B	24	25	10	19	
					5.5
Highly disturbed (HD)					
4A	16	20	6	12	3
4B	<1	0	<1	1	2
Non-soil (NS)	8	5	4	8	5.5
Total	99	100	100	100	100

[a]% disturbance on a stand wide (SW), harvested strip (HS) basis, and non-harvested strip (US).

measured by slope position whereas a wider range (0.54 and 0.92 MPa) in CI value was noted by future management prescription with higher CI detected in the DC TRT. An ANOVA did not detect significant differences for bulk density, SMC, or CI by slope or future TRT area. The slight differences in bulk density, SMC and CI values by slope position and future management prescription may be the result of variability in soil texture in the study site. Although soil textural analysis and classification indicated the texture as loam, a higher percentage of sand was present in the top slope position that decreased with slope position. The subtle changes in soil texture may have influenced the soil physical properties measured in the pre-harvest condition. And as expected, no soil disturbance was present.

3.2. Post-harvest

3.2.1. Soil DICLs

Soil surface DICLs tabulated within each silvicultural prescription indicated the greatest impacts to be associated with CC and DC TRTs on a SW basis (Table 2). DICL percentages were similar in CC and DC TRTs with 20% and 18% recorded as UNT, 57% and 55% as SD, and 20% and 17% recorded as HD, respectively. A small percentage of each TRT was classified as NS indicative of the presence of heavy slash or rocks that prevented determination of a DICL. Soil surface disturbance was lowest in the SC TRT with approximately 62% classified as UNT and 28% and 6% as SD and HD, respectively, on a SW basis (SC/SW). The higher percentage of disturbance classified as UNT is undoubtedly due to the inclusion of undisturbed strips in the SC/SW assessment; however, disturbance patterns tabulated for harvested portions of the SC TRT (SC/HS) resembled CC and DC TRTs. Disturbance was present in the US (SC/US) as indicated by the small percentage of SD and HD classes.

3.2.2. Soil physical response

Soil physical properties responded to the implementation of each management prescription and differences were detected among TRTs according to response variables (Table 3). Bulk density was greatest in the soil surface layer of CC approximately 1.13 $Mg\,m^{-3}$ and lowest in CON. The DC TRT impacted soil surface bulk density but the increase was less than CC in spite of similar disturbance

Table 3
Postharvest soil response at two depth increments to three alternative management prescriptions in an upland hardwood stand in northern Alabama, USA

Treatment[a]	Depth (m)	Bulk density ($Mg\,m^{-3}$)	Soil moisture content (w/w) (%)
CON	0.0–0.1	0.93 (19.3)c[b]	27.2 (54.6)
	0.1–0.2	1.30 (13.4) B	19.8 (28.6)
CC	0.0–0.1	1.13 (20.6) a	33.1 (36.4)
	0.1–0.2	1.31 (19.8) A	22.9 (31.9)
DC	0.0–0.1	1.05 (20.7) b	35.3 (40.3)
	0.1–0.2	1.36 (15.4) AB	24.0 (36.0)
SC			
SW	0.0–0.1	1.04 (21.3) bc	28.0 (53.2)
	0.1–0.2	1.35 (15.4) AB	24.7 (28.9)
HS	0.0–0.1	1.03 (21.3) bc	31.1 (48.2)
	0.1–0.2	1.36 (14.5) AB	24.2 (28.9)
US	0.0–0.1	1.05 (21.4) bc	25.0 (57.2)
	0.1–0.2	1.33 (16.6) AB	25.4 (29.1)

[a]Treatments: CON = control; CC = clear cut; DC = deferment cut; SC = strip cut; SW = stand wide; HS = harvested strip; US = non-harvested strip.

[b]Number in parentheses is coefficient of variation (CV); lower case letters indicate significant differences at the $\alpha = 0.10$ level in the 0.10–0.20 m depth and capital letters indicate significant differences at the $\alpha = 0.10$ level in the 0.10–0.20 m depth.

patterns. Bulk density values in SC were analyzed by considering the entire dataset on a SW basis (SC/SW) and then analyzing the dataset as two separate sections: HS (SC/HS) versus US (SC/US). Bulk density on a SW (SC/SW) basis was less than CC and similar to DC; in addition, there were no differences in bulk density when the dataset was examined by harvest condition (SC/HS vs. SC/US). In the subsurface layer (0.10–0.20 m), bulk density levels were approximately 1.30 $Mg\,m^{-3}$ or higher in all TRTs with DC and SC (all datasets) measuring approximately 1.35 $Mg\,m^{-3}$ with CC slightly less.

Statistical evaluation (ANOVA) of post-harvest bulk density data indicated that the main effects of TRT (TRT) ($P = 0.02$) and depth (DPTH) ($P < 0.001$) were significant sources of variation for bulk density (Table 4). The interaction term of TRT × DPTH was not significant.

SMC ranged between 25% and 35% by weight in the soil surface layer with the highest levels measured in DC. Subsurface SMCs were lower than surface layers and ranged between 20% and 25% with the highest quantities measured in SC/US. TRT was not a significant source of variation for SMC whereas DPTH was significant ($P < 0.0001$) (Table 4); the interaction of TRT × DPTH was not significant.

CI values increased with depth in general and in response to each management prescription compared to the non-harvested condition at each depth increment (CON) (Fig. 2). CI values were elevated to the highest level in DC followed by CC whereas CON measured the lowest. A comparison of CI values in SC indicated relatively similar values regardless of how the data were evaluated; SC/US was slightly elevated compared to SC/SW and SC/HS. TRT ($P = 0.0013$), DPTH ($P < 0.0001$) and the interaction of TRT × DPTH (< 0.0001) were significant sources of variation for CI values (Table 4). All TRTs differed significantly from each other as indicated by the comparison of regression coefficients (Table 5); no significant differences were detected among the three SC TRTs. The influence of DPTH and the interaction between TRT × DPTH was taken into account in the comparison of regression coefficients.

The results generally support the belief that clear-cutting can have a substantial impact on site conditions as evidenced by the change in bulk density and soil strength. The resulting increase in bulk density was associated with an increase in soil moisture presumably due to the change in soil volume. However, the DC TRT exceeded CC in soil

Table 4
Probability (Pr > F) of statistical significance of main effects and interactions on select soil physical properties subjected to three alternative management prescriptions in an upland hardwood stand, northern Alabama, USA

	Soil physical properties		
	Bulk density	Soil moisture content	Cone index
Main effects			
Treatment (TRT)	0.0204	0.8667	0.0013
Disturbance class (DICL)	0.5806	0.0386	<0.0001
Depth (DPTH)	<0.0001	<0.0001	<0.0001
Interactions			
TRT × DICL	0.0159	0.4333	0.8343
TRT × DPTH	0.2435	0.6845	<0.0001
DICL × DPTH	0.0421	0.4722	0.0002

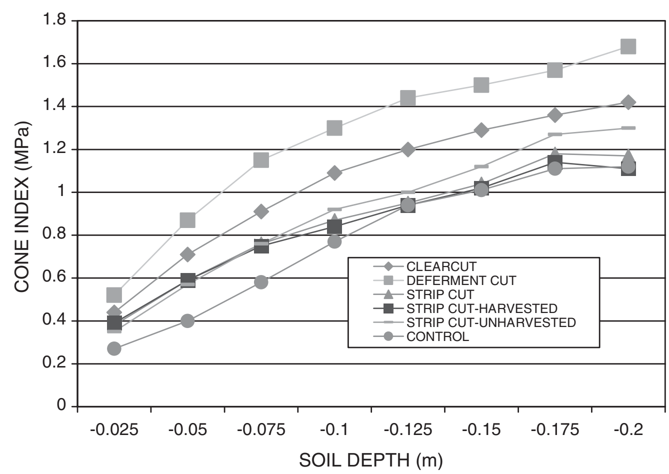

Fig. 2. Cone index response (0.0–0.20 m) by treatment of a hardwood stand subjected to three alternative management prescriptions in northern Alabama, USA.

Table 5
Summary of statistical probabilities (Pr > F) of significant differences among treatments of cone index measurements in an upland hardwood stand in northern Alabama, USA

Treatment	Treatment					
	Control (CON)	Clear-cut (CC)	Deferment cut (DC)	Strip cut (SC)[a]		
				SW	HS	US
CON	1.0000	<0.0001	<0.0001	0.0061	0.0173	0.0019
CC	0.0004	1.0000	0.0066	0.0029	0.0013	0.0067
DC	0.0001	0.0244	1.0000	0.0005	0.0003	0.0008
SC						
SW	0.0090	0.0002	<0.0001	1.0000	0.3297	0.3497
HS	0.0236	<0.0001	<0.0001	0.3241	1.000	0.0473
US	0.0035	0.0007	<0.0001	0.3701	0.0554	1.0000

[a]Strip cut treatments: SW = stand wide; HS = harvested strip; US = non-harvested strip.

Table 6
Bulk density ($Mg\,m^{-3}$) of two soil depth increments by disturbance class in an upland hardwood stand in northern Alabama, USA subjected to three alternative management prescriptions

Disturbance class[a]	Treatment					
	Depth (m)	Clear-cut	Deferment cut ($Mg\,m^{-3}$)	Strip cut[b]		
				SW	HS	US
Untrafficked						
UNT	0.0–0.1	1.08	0.99	1.08	1.05	1.10
	0.1–0.2	1.26	1.37	1.37	1.35	1.38
Slightly disturbed						
2A	0.0–0.1	1.03	1.06	1.08	1.12	1.00
	0.1–0.2	1.29	1.38	1.35	1.37	1.32
2B	0.0–0.1	1.17	1.12	0.92	0.83	1.07
	0.1–0.2	1.30	1.38	1.36	1.47	1.12
Highly disturbed						
4A	0.0–0.1	1.26	1.03	0.98	0.99	0.95
	0.1–0.2	1.65	1.31	1.25	1.19	1.36
4B	0.0–0.1	1.56	—	0.75	—	
	0.1–0.2	1.68	—	1.39	—	1.39

[a]Disturbance classes: UNT = undisturbed; 2A = trafficked with litter; 2B = trafficked with litter displaced; 4A = depression <15 cm; 4B = depression >15 cm.
[b]Strip cut treatments: SW = stand wide basis; HS = harvested strips; US = non-harvested strips.

strength response and may be indicative of the differences in the implementation of each TRT. Machine movements in DC required more trips with lighter loads compared to CC and may have contributed to the different trends observed in bulk density and CI measurements.

3.2.3. Soil physical response by DICL

Bulk density was altered in response to the implementation of each management prescription and varied by DICL (Table 6). Bulk density levels in the soil surface layer ranged between 0.75 $Mg\,m^{-3}$ in highly disturbed sites of non-harvested zones of SC (SC/US) (DICL 4B) and 1.56 $Mg\,m^{-3}$ in deeply rutted sites (DICL 4B) of CC. Bulk density levels in the subsurface (0.10–0.20 m) layer were slightly higher relative to untrafficked sites (DICL UNT) and were highest in the highly disturbed sites of CC (DICLs 4A and 4B). DICL was not a significant source of variation for bulk density whereas the interaction of TRT × DICL ($P = 0.0159$) and DPTH × DICL ($P = 0.0421$) were significant (Table 4).

SMC was consistently higher in the 0.0–0.10 m soil layer than in the 0.10–0.20 m soil layer for each management and DICL combination with one exception (Table 7). SMC was generally lower in the soil surface layer where machine traffic traversed the site (CC, DC, and SC/HS) with a few exceptions. No clear pattern emerged in the subsoil layers as to the impact of management prescription on final SMC. DICL ($P = 0.0386$) was a significant source of variation for SMC while the interaction of TRT × DICL ($P = 0.4333$) and DPTH × DICL ($P = 0.4722$) were not significant (Table 4).

Table 7
Soil moisture content (w/w) (%) of two soil depth increments by disturbance class in an upland hardwood stand in northern Alabama, USA subjected to three alternative management prescriptions

Disturbance class[a]	Treatment					
	Depth (m)	Clear cut	Deferment cut (%)	Strip cut [b]		
				SW	HS	US
Untrafficked						
	0.0–0.1	36.5	35.0	25.7	30.9	22.6
	0.1–0.2	24.3	23.1	25.5	25.1	25.9
Slightly disturbed						
2A	0.0–0.1	39.4	31.3	26.4	26.2	26.8
	0.1–0.2	21.8	20.0	23.4	24.8	17.5
2B	0.0–0.1	36.1	31.2	38.2	44.7	26.7
	0.1–0.2	25.4	38.2	21.7	19.4	25.6
Highly disturbed						
4A	0.0–0.1	35.7	37.2	26.1	24.1	29.4
	0.1–0.2	13.4	28.6	18.8	18.8	—
4B	0.0–0.1	21.9	—	—	—	—
	0.1–0.2	17.2	—	20.6	—	20.6

[a]Disturbance classes: Untrafficked = no sign of traffic; 2A = trafficked with litter; 2B = trafficked with litter displaced; 4A = depression <0.15 m; 4B = depression >0.15 m.
[b]Strip cut treatments: SW = stand wide basis; HS = harvested strips; US = non-harvested strips.

The study indicated a trend between bulk density and DICL in surface and subsurface soil layers of CC that was not evident in other TRTs. Maximum bulk density of both soil layers was noted in slightly disturbed classes of DC and in the harvested strip of SC (SC/HS) whereas lower levels were detected in the highly disturbed sites of DC and all combinations in SC. Mean comparisons of management and DICL combinations for bulk density did not clarify the results any further than already highlighted. A potential explanation for the observed results may be related to differences in traffic patterns in the implementation of DC and SC TRTs versus CC. Pre-harvest site conditions did not influence post-harvest results when examined for statistical significance. DICL was significant for SMC but the interaction of management prescription and DICL did not contribute to the differences measured in the TRT areas.

CI values varied by DICL and typically increased in both depth increments as traffic intensity increased regardless of management TRT (Table 8). Significant differences were detected among TRTs as already indicated taking into account DPTH and TRT × DPTH (Table 4). DICL ($P = <0.0001$) was a significant source of variation for CI as well as DPTH × DICL ($P = 0.0002$) while no significance was found for the interaction of TRT × DICL ($P = 0.8343$) (Table 4). Comparison of CI values by DICL indicated significant differences among DICLs with the exception of 2B and 4B (Table 9). DICL 4A was observed to have the highest CI values followed by DICLs 2B and 4B and 2A and UNT (Fig. 3). Although differences were detected by DICL, the levels measured never exceeded 1.6 MPa, well below the 2.5 MPa level considered to limit root growth.

4. Discussion

Soil disturbance occurs extensively as a result of machine traffic traversing an area during harvest and thinning operations. Soil disturbance occurred on approximately 75% of the CC and DC TRTs and 67% of SC/HS as indicated through the tabulation of soil DICLs. Previous studies in the southeastern USA have reported soil disturbance percentages that ranged between 16% and 65% [5,6,16,21,22]. Results of DICL tabulations are influenced by the method of assessment and the spacing between transects [23]. Soil disturbance tabulations in this study utilized the methodology (point transect method) and spacing recommended by McMahon [23] that were shown to reasonably assess soil disturbance patterns in a harvested pine stand. A recent study of machine trafficking during clear-cutting operations in a loblolly pine stand in Alabama utilizing GPS technology reported visual estimation of soil disturbances to overestimate the degree of disturbance from skid trails and decks while underestimating the area that remained undisturbed [24]. The results obtained in this study tabulated slightly more disturbance than was estimated by monitoring via GPS.

Soil disturbance percentages approaching 75% in CC, DC, and SC/HS indicated that a high degree of trafficking occurred in order to achieve the management objectives. A majority of the disturbance categories were tabulated as slightly disturbed (2A and 2B) indicating at least half of each TRT area was exposed to machine trafficking in the course of implementing the management prescription. Highly disturbed areas (4A and 4B) occurred on a lower percentage of the area when compared with the slightly disturbed areas. The lower occurrence of highly disturbed

Table 8
Cone index values (MPa) of two soil depth increments by disturbance class in an upland hardwood stand in northern Alabama, USA subjected to three alternative management prescriptions

Disturbance class[a]	Treatement					
	Depth (m)	Clear cut	Deferment cut (Mpa)	Strip cut[b]		
				SW	HS	US
Untrafficked						
	0.0–0.1	0.69	0.81	0.63	0.52	0.68
	0.1–0.2	1.37	1.45	1.17	1.05	1.24
Slightly disturbed						
2A	0.0–0.1	0.67	0.81	0.58	0.63	0.54
	0.1–0.2	1.23	1.45	1.00	1.04	1.00
2B	0.0–0.1	0.87	1.01	0.69	0.75	0.52
	0.1–0.2	1.38	1.61	1.19	1.28	0.95
Highly disturbed						
4A	0.0–0.1	0.99	1.17	0.97	0.94	1.26
	0.1–0.2	1.54	1.72	1.27	1.28	1.20
4B	0.0–0.1	1.07	—	0.73	—	0.73
	0.1–0.2	1.80	—	1.11	—	1.11

[a]Disturbance classes: Untrafficked = no sign of traffic; 2A = trafficked with litter; 2B = trafficked with litter displaced; 4A = depression <0.15 m; 4B = depression >0.15 m.
[b]Strip cut treatments: SW = stand wide basis; HS = harvested strips; US = non-harvested strips.

Table 9
Summary of probabilities ($Pr > F$) of significant differences among disturbance classes of cone index measurements in an upland hardwood stand subjected to three alternative management prescriptions in northern Alabama, USA

Disturbance class	Disturbance class				
	2A	2B	4A	4B	UND
2A	1.0000	<0.0001	<0.0001	<0.0001	0.0856
2B	0.0027	1.0000	<0.0001	0.1426	0.0269
4A	<0.0001	<0.0001	1.0000	0.0001	<0.0001
4B	0.0151	0.5335	0.0460	1.0000	0.0416
UND	0.0540	0.0004	<0.0001	<0.0001	1.0000

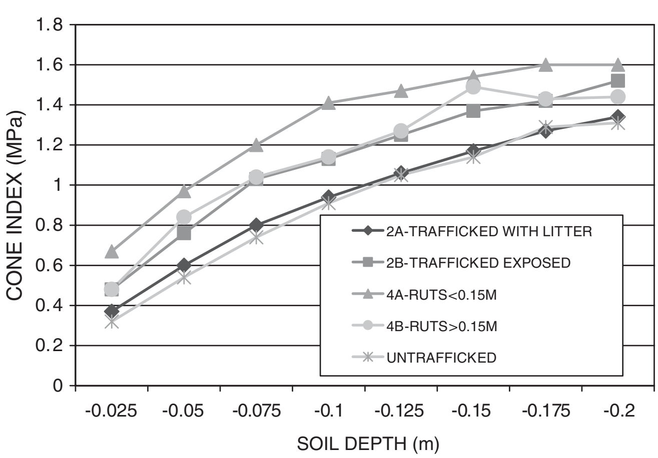

Fig. 3. Cone index response (0.0–0.20 m) by disturbance class of a hardwood stand subjected to three alternative management prescriptions in northern Alabama, USA.

areas in CC and DC may be the result of limiting skidder traffic to primary skid trails while a slightly higher percentage in DC may be the result of more traffic, dispersed over a wider area in DC to accomplish the stated management objectives. Time and productivity data associated with implementation of each management prescription have been previously summarized [25].

Trafficking of soils typically alters soil physical properties. Bulk density increased in response to each TRT compared to CON with the greatest change detected in CC. Bulk density responses may be the result of the number of machine passes, the weight of each load being removed or a combination of these factors [3,4,26,27]. The number of machine passes has been correlated to the increased bulk density in Coastal Plain and Piedmont soils under a constant load [28,29]. Equipment weight alone or in combination with weight due to loads can result in significant degree of compaction [26]. Skidding productivity data collected in this study indicated the highest wood volumes removed in each cycle occurred in CC while lower volumes were removed from DC and SC [24]. The bulk densities measured in CC may be highest as a result of heavier loads removed from each TRT area while more passes but lighter loads may have had a lesser impact in DC. The bulk density data collected for SC/HS was similar to CC in the percentages and types of soil disturbance but bulk density levels were lower than CC. The relationship among machine characteristics, machine movements, weight of stems per cycle, and soil conditions at the time of harvest require more in depth evaluation to determine the factors that contributed to changes in bulk density.

Soil strength as indicated by CI measurements increased with depth and was influenced by management prescription. Soil strength was elevated to its highest level in DC rather than CC as might be expected. Soil strength has been previously reported to increase in response to increased loads and machine passes with the impact transmitted to deeper portions of the soil profile as weight and number of passes increased [26,30]. The results of this study may indicate the influence of number of machine passes rather than load weight as the most important factor in increase in soil strength in DC. Previous investigations have reported increased soil strength in response to increased machine passes with soil strength observed to stabilize after a select number of passes and the rate of change to decline with repeated passes [7,8,31,32]. Although there were no significant differences among the TRTs in the pre-harvest phase, the CI status was slightly higher in DC and may have contributed to higher CI values in relation to CC.

5. Summary

Soil disturbances related to the implementation of three alternative management prescriptions were tabulated as well as measurement of changes in soil physical properties. The final tabulations indicated that CC, DC and SC/HS were similar in their distribution of soil disturbances; examination of the SC TRT on a SW basis and in US indicated higher percentages of no disturbance, as would be expected.

Soil physical response varied by property but, in general, as disturbance intensity increased, soil physical properties responded accordingly. Differences were noted for bulk density and soil strength among TRTs with bulk density highest in CC and soil strength highest in DC. These differences were postulated to result from differences in the trafficking patterns required to fulfill management objectives. The final compaction status of a trafficked site would reflect soil conditions at the time of interaction with machine systems [33–35]. To truly understand soil response to machine trafficking a more in-depth evaluation of the interaction between soil properties and machine systems is required.

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